Inspiratory Pressure Support Prevents Diaphragmatic Fatigue during Weaning from Mechanical Ventilation[1-4]

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SUMMARY Persistent inability to tolerate discontinuation from mechanical ventilation is frequently encountered in patients recovering from acute respiratory failure. We studied the ability of inspiratory pressure support, a new mode of ventilatory assistance, to promote a nonfatiguing respiratory muscle activity in eight patients unsuccessful at weaning from mechanical ventilation. During spontaneous breathing, seven of the eight patients demonstrated electromyographic signs of incipient diaphragmatic fatigue. During ventilation with pressure support at increasing levels, the work of breathing gradually decreased ($p < 0.02$) as well as the oxygen consumption of the respiratory muscles ($p < 0.01$), and electrical signs suggestive of diaphragmatic fatigue were no longer present. In addition, intrinsic positive end-expiratory pressure was progressively reduced. For each patient an optimal level of pressure support was found (as much as 20 cm H_2O), identified as the lowest level maintaining diaphragmatic activity without fatigue. Above this level, diaphragmatic activity was further reduced and untoward effects such as hyperinflation and apnea occurred. When electrical diaphragmatic fatigue occurred, the activity of the sternocleidomastoid muscle was markedly increased, whereas it was minimal when the optimal level was reached.

We conclude that in patients demonstrating difficulties in weaning from the ventilator: (*1*) pressure support ventilation can assist spontaneous breathing and avoid diaphragmatic fatigue (pressure support allows adjustment of the work of each breath to provide an optimal muscle load); (*2*) clinical monitoring of sternocleidomastoid muscle activity allows the required level of pressure support to be determined to prevent fatigue. AM REV RESPIR DIS 1989; 139:513-521

Introduction

Inability to tolerate discontinuation of mechanical ventilation is reported to occur in as much as 20% of mechanically ventilated patients (1). In patients recovering from acute respiratory failure, diaphragmatic fatigue is probably a major cause of failure to wean from mechanical ventilation (2-4). Unfavorable conditions such as a high airway resistance and lung hyperinflation may occur, causing an excessive work load on the respiratory muscles.

The strategy for weaning these patients is an important issue for physicians providing respiratory care. Periods of T-tube trial followed by mechanical ventilation have been proposed to promote nonfatiguing respiratory muscle activity (5, 6). However, T-tube ventilation requires constant monitoring of the patient and necessitates the vigilant presence of well-trained hospital personnel. Several ventilatory modalities allowing spontaneous breaths such as intermittent mandatory ventilation and the assist-control mode can be used to assist respiration during the weaning period, and they have been proposed to reduce this surveillance requirement. Intermittent mandatory ventilation has proved to be of no benefit to respiratory muscles and may delay the time of extubation (6) and augment the work of breathing (7, 8). Studying the assist-control mode, Marini and coworkers (9, 10) showed that significant exertion of the respiratory musculature persists throughout each patient-initiated ventilator cycle, often at levels taxing the ventilatory reserve. Thus, this mode of ventilation must be used with great caution in patients experiencing difficulties in tolerating discontinuation from mechanical ventilation.

Inspiratory pressure support is a recent mode of ventilatory assistance designed to maintain a constant preset positive airway pressure during spontaneous inspiration. The respiratory rate, tidal volume, and inspiratory time are regulated by the patient, and the work performed by the inspiratory muscles, especially the diaphragm, is substantially reduced (11). A key feature of this mode of ventilatory assistance is that it maintains and supports the patient's inspiratory effort (12, 13). Thus, the patient does not oppose the mechanical inspiratory assistance, and while maintaining some inspiratory muscle activity it may provide graded training of the respiratory muscles during weaning. However, whether the inspiratory work of breathing is decreased during pressure support, and to what extent, remains to be determined since (*1*) initiation of inspiration is a major determinant of the magnitude of the inspiratory effort (because pressure support necessitates the opening of the demand-valve, the inspiratory work may remain high), and the presence of intrinsic positive end-expiratory pressure (PEEP) may also induce a supplementary inspiratory muscle effort (13, 14); (*2*) pressure support can increase minute ventilation, thus increasing the total work per unit of time; (*3*) it is difficult to predict the alveolar pressure generated by pressure support with regard to the nonlinear resistant behavior of the endotracheal tube.

At high levels of pressure support (as much as 41 cm H_2O in the study of MacIntyre [12]), an almost passive inflation occurs. Tidal volume then depends upon lung compliance and may be excessive, with the potential risks of hyperinflation. Thus, although this mode appears potentially useful during the weaning period, employing pressure support ventilation requires defining the most beneficial ("optimal") level in each patient.

The aims of this study were (*1*) to learn if pressure support ventilation can prevent diaphragmatic fatigue by diminishing the work of breathing as well as the oxygen consumption of the respiratory

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muscles in patients weaning from mechanical ventilation, and (2) to search for the optimal level of pressure support in each patient, defining it as the level that would maintain a substantial diaphragmatic activity without inducing fatigue.

Methods

We studied eight patients recovering from acute respiratory failure in whom previous attempts at weaning from mechanical ventilation had failed. Pertinent clinical and respiratory features of the patients are listed in table 1. All the patients satisfied the following criteria for weaning during mechanical ventilation (1, 15): inspiratory force greater than 25 cm H_2O, vital capacity > 10 ml/kg, arterial oxygen saturation > 90% at F_{IO_2} 0.4. However, they could not tolerate prolonged periods of spontaneous breathing via a T-piece with supplemental oxygen when tested the day preceding the study. In each patient, one or more of the following occurred by the end of this previous weaning trial: a respiratory rate > 40 breaths/min, paradoxical abdominal motion, heart rate greater than 140 beats/min, Pa_{CO_2} < 55 mm Hg, increase in Pa_{CO_2} of more than 10 mm Hg in patients with chronic CO_2 retention, or Pa_{CO_2} > 45 mm Hg for the others.

Each patient was evaluated during a period of controlled mechanical ventilation (CMV) and during spontaneous breathing with pressure support ventilation. Four successive levels of pressure support were used in the following order: (1) zero cm H_2O (PS 0) (equivalent to spontaneous breathing via the ventilator circuitry), (2) 10 cm H_2O (PS 10), (3) 15 cm H_2O (PS 15), and (4) 20 cm H_2O (PS 20) delivered via a Siemens Servo-Ventilator 900 C (Siemens, Berlin, FRG). The pressure support mode of this ventilator operates as follows: (1) inspiration is initiated by the opening of a scissor valve (the trigger sensitivity was set to its minimal level, zero cm H_2O); (2) a preset pressure level is maintained by a servo loop in the ventilator that continuously adjusts inspiratory flow, providing a decelerating gas flow with an airway pressure plateau; (3) exhalation begins when inspiratory flow falls below 25% of the peak flow or when airway pressure exceeds the preset pressure level by 3 cm H_2O; (4) expiration follows without pressure support.

All four levels of pressure support were studied on the same day. Each level was used for a trial period of 20 min. All recordings and measurements were obtained during the last 5 min of each trial. CMV was resumed between each test measurement for at least 30 min, a period sufficient in all cases to allow the heart rate to return to its pretrial value. All recordings and measurements during CMV were obtained when the respiratory muscles were at rest (see below). Each patient was placed in a semirecumbent position, which was maintained during the study. Patients received endotracheal suctioning whenever necessary. No sedatives or narcotics were administered. The F_{IO_2} was constant for each patient during the study. This study was approved by the Ethical Committee of the Société de Réanimation de Langue Française. Informed consent was obtained from each patient prior to study.

Measurements

To compute respiratory mechanics all signals were digitized at 32 Hz and sampled by an Apple IIe microprocessor system. Airflow was measured with a heated Fleisch no. 2 pneumotachygraph connected to a pressure transducer (Validyne MP 45 ± 2 cm H_2O; Validyne Corp., Northridge, CA). Tidal volume (V_T) was obtained by integrating the flow signal. Esophageal pressure (Pes) was measured using a thin latex balloon filled with 0.5 ml of air and positioned by the usual method (16); the balloon was connected to a differential pressure transducer (Validyne MP 45 ± 70 cm H_2O). Appropriate placement of the esophageal balloon was verified by an occlusion test (17). Airway pressure was recorded at the distal end of the endotracheal tube with a differential pressure transducer (Sensym LDX 06001 ± 70 cm H_2O).

Inspiratory work of breathing was obtained from a Campbell's diagram by computing the area subtended by (1) the curve of Pes versus lung volume during inspiration (the values of Pes at points of zero flow were determined as the beginning and the end of inspiration), and (2) the relaxation curve of the chest wall passing through the elastic recoil pressure of the chest wall at end exhalation (18). This curve was obtained by plotting Pes against V_T during controlled mechanical ventilation while the respiratory muscles were assumed to be in relaxation as assessed by electromyographic measurements (see below). This relaxation curve was assumed to be linear and extrapolated for the volume corresponding to each breath. Elastic recoil pressure of the chest was calculated graphically on Pes tracings as the value of the negative Pes deflection that occurred before the beginning of inspiratory flow. Indeed, when intrinsic PEEP is present at end exhalation, the respiratory muscles have first to counteract this positive pressure before inspiration can start. The work of breathing was expressed either as the work per liter of ventilation ($W/\dot{V}$) or as the power (work per unit of time, $\dot{W}$). For each variable the mean value of at least 10 sequential breaths was determined.

Activity of the respiratory muscles was assessed by two means. First, transdiaphragmatic pressure (Pdi) was measured as gastric pressure minus Pes using a differential transducer (Validyne MP 45 ± 70 cm H_2O). Gastric pressure was measured with a thin latex balloon filled with 1 ml of air and positioned in the stomach. Pdi swings were calculated as peak inspiratory minus peak expiratory pressure.

TABLE 1

CLINICAL AND RESPIRATORY CHARACTERISTICS OF THE PATIENTS

Patient No.	Sex	Age (yr)	Pa_{O_2}* (mm Hg)	Pa_{CO_2}* (mm Hg)	F_{IO_2}†	CL (ml/cm H_2O)	MIP (cm H_2O)	Duration of Mechanical Ventilation (days)	Diagnosis
1	M	65	103	30	0.25	58	55	21	Meningitis, Pneumonia
2	M	78	58	44	0.40	46	33	17	COPD, Congestive heart failure
3	F	72	60	35	0.25	24	35	25	COPD
4	M	42	89	40	0.25	91	30	11	Pneumonia
5	F	54	66	37	0.30	27	38	9	Postoperative obesity
6	F	71	150	30	0.35	52	25	18	Pulmonary embolism, Pneumonia, Obesity
7	M	62	80	35	0.40	24	40	21	COPD
8	F	59	81	37	0.30	62	28	34	COPD, Congestive heart failure

Definition of abbreviations: CL = dynamic lung compliance computed during spontaneous breathing from esophageal pressure minus airway pressure; MIP = maximal negative inspiratory pressure recorded during airway occlusion; COPD = chronic obstructive pulmonary disease.

* Measured during control mechanical ventilation.

† Applied during mechanical ventilation.

Second, the electrical activity of the diaphragm (EMG) was recorded using a bipolar esophageal electrode (DISA 13K63) and conditioned with a DISA 15CO1 electromyograph amplifier (band-pass between 20 Hz and 1 kHz). The electrode was passed via one nostril and swallowed into the stomach. The electrode was then positioned to yield maximal electromyographic activity while the subject breathed spontaneously, and fixed at the nasal orifice by tape. Stabilization of the catheter with a gastric balloon was not done because it offers no advantage over securing the catheter at the nose in sitting humans (19). Signals were recorded on a magnetic tape for subsequent processing. Analysis of the signal was as follows: the recorded EMG signal was band-pass filtered, rectified, and integrated by a "leaky integrator" with a time constant of 0.1 s. The integrated components were recorded on a strip chart recorder with amplitude calibrated in arbitrary units. Three band-pass filters were used. The first filter was set between 20 Hz and 1 kHz, providing the total integrated diaphragmatic activity (Edi). The subsequent two filters had a band-pass range between 20 and 47 Hz for the diaphragmatic low frequency electrical component and between 150 and 350 Hz for the high frequency component in order to determine the ratio of high to low frequency components (H/L) (20). The time course of the H/L ratio was then analyzed; this ratio was computed over 10 inspirations at the end of each trial and was expressed as a fraction of the H/L value measured at the beginning of each trial. A reduction to 80% or less of the initial value defined incipient diaphragmatic fatigue as previously described (20, 21). EKG artifacts were removed by sampling the EMG between QRS complexes.

The electrical activity of the sternocleidomastoid muscle was measured with surface electrodes (DISA 13K60). A band-pass filter from 20 Hz to 1 kHz allowed determining the integrated electrical activity of this muscle (Esm). Esm was expressed as a fraction of the maximal spontaneous electrical activity measured during PS 0. Contraction of the sternomastoid muscle was assessed by palpating the muscle in the neck.

Oxygen consumption. Inspiratory gas samples were taken from the inspiratory line of the ventilator. Expiratory gas samples were drawn from a Douglas bag collecting expired gas over a 2-min period with expired minute volume recorded during the same period. Oxygen and carbon dioxide levels were measured with an ABL 30 (Radiometer, Copenhagen, Denmark). Oxygen consumption ($\dot{V}O_2$) was calculated using the following equation:

$$\dot{V}O_2 = \dot{V}E\ (\text{STPD}) \times \left[\frac{FIO_2\,(1 - FEO_2 - FECO_2)}{1 - FIO_2 - FICO_2} - FEO_2\right]$$

where FIO_2 and $FICO_2$ are inspired oxygen and carbon dioxide fractions, respectively, FEO_2 and $FECO_2$ represent expired gas concentrations, and $\dot{V}E$ is minute ventilation.

The oxygen cost of breathing (COB) was defined as the difference between the $\dot{V}O_2$ measured during assisted spontaneous breathing and the $\dot{V}O_2$ during controlled mechanical ventilation (24). In previous studies, we found unsatisfying correlations comparing these results with measurements obtained by the Fick method when the FIO_2 was equal to or higher than 0.4. Consequently, we did not measure the oxygen consumption of two patients (Patients 2 and 7).

Arterial blood gas tensions were analyzed with an ABL 30 (Radiometer). Heart rate (HR) and systolic blood pressure (BP) were continuously monitored.

All the data are presented as mean ± SD. Data were analyzed by a two-way analysis of variance (ANOVA), and the differences between groups were detected using Tukey's test. Linear regression analysis was used for correlation.

Results

Controlled Mechanical Ventilation

During all periods of CMV, we detected no electrical activity of the respiratory muscles. Accordingly, the value of Pdi obtained was always near zero cm H_2O. The work of breathing during CMV was also nil since the esophageal pressure curve during CMV, i.e., the relaxation curve of the chest wall, was taken as reference.

Spontaneous Breathing without Pressure Support

At the end of a 20-min period of spontaneous breathing via the ventilator circuitry without pressure support (PS 0), all patients except one (Patient 1) exhibited a marked reduction of the H/L ratio to 59 ± 14% (figure 1), indicating that because of excessive loading, diaphragmatic fatigue would ensue in all these patients. All these patients exhibited concomitantly a noticeable mechanical and electrical activity of the sternomastoid muscle.

In comparison with CMV, after 20 min of spontaneous breathing there were considerable modifications of respiratory mechanics, gas exchange and hemodynamic parameters. We measured a decreased VT (from 544 ± 125 to 377 ± 80 ml, $p < 0.001$) and an increased respiratory rate (RR) (19 ± 1 to 31 ± 8 breaths·min^{-1}, $p < 0.001$) without a change in $\dot{V}E$ (10.4 ± 1.0 to 11.2 ± 2.2 L·min^{-1}). The $PaCO_2$ increased from 36 ± 5 to 45 ± 8 mm Hg ($p < 0.001$). The $\dot{V}O_2$ increased from 210 ± 83 to 288 ± 49 ml·min^{-1} ($p < 0.001$), and consequently the mean COB amounted to 27% of the $\dot{V}O_2$ (range, 10 to 59%). Mean heart rate (HR) increased by 18 beats·min^{-1} (range, 2 to 55 beats·min^{-1}, $p < 0.001$), and mean systolic blood pressure (BP) increased by 27 mm Hg (range, 5 to 60 mm Hg, $p < 0.001$).

Breathing with Inspiratory Pressure Support

In comparison with spontaneous breathing (PS 0) when increasing levels of pressure support (PS 10, PS 15, PS 20) were provided, there was an increased VT and a decreased RR, a decreased $PaCO_2$ and a marked reduction of the work of

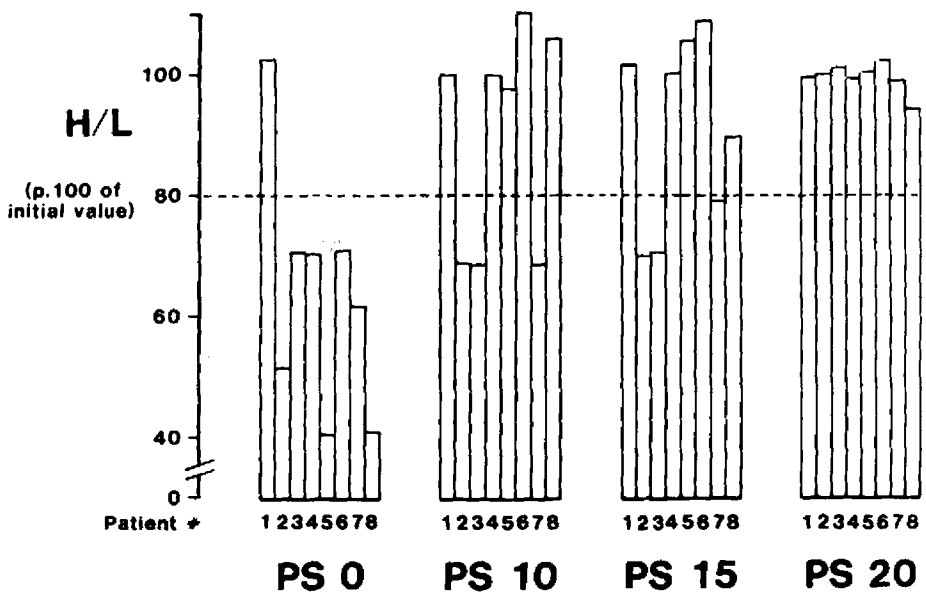

Fig. 1. Individual values of the H/L ratio at the end of each 20 min period, expressed as a fraction of its initial value, at the four levels of pressure support ventilation. The dashed line represents the threshold of fatigue.

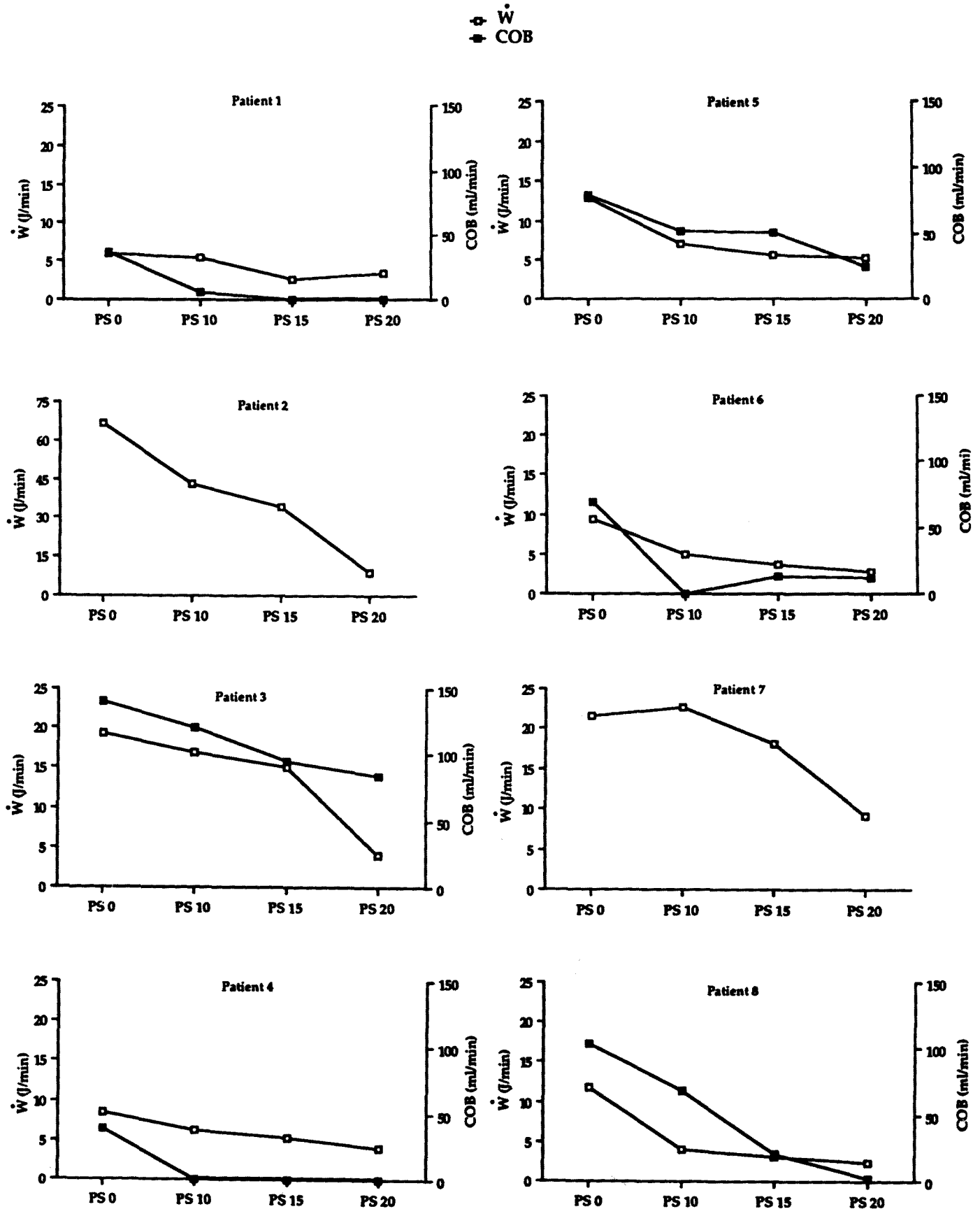

Fig. 2. Individual plots of power of breathing (Ẇ) and cost of breathing (COB) against pressure support level for each of the eight patients or for six of the eight for the COB.

TABLE 2

CHANGES IN VENTILATORY PARAMETERS, GAS EXCHANGE, AND TRANSDIAPHRAGMATIC PRESSURE WITH INCREASING LEVELS OF PRESSURE SUPPORT*

	Pressure Support Levels (cm H_2O)			
	0	10	15	20
VT, ml	377 ± 80	459 ± 63‡	491 ± 82‖	533 ± 131¶
RR, min^{-1}	31 ± 8	29 ± 8	26 ± 8¶	24 ± 7¶
$\dot{V}E$, $L \cdot min^{-1}$	11.2 ± 2.2	13.0 ± 2.9§	13.1 ± 2.9§	12.3 ± 2.3
Pdi, cm H_2O	21 ± 12	14 ± 11¶	10 ± 8¶	9 ± 8¶
$PEEP_i$, cm H_2O†	2.7 ± 1.7	1.5 ± 1.2§	0.9 ± 1.2§	0.7 ± 0.7§
Pa_{O_2}, mm Hg	76 ± 18	79 ± 19	79 ± 16	83 ± 19
Pa_{CO_2}, mm Hg	45 ± 8	40 ± 6§	39 ± 5‖	36 ± 6¶
$\dot{V}O_2$, $ml \cdot min^{-1}$	288 ± 49	241 ± 55‖	235 ± 48‖	213 ± 54¶
$\dot{W}$, $J \cdot min^{-1}$	19.5 ± 19.7	13.8 ± 13.6	10.9 ± 10.9§	5.0 ± 2.6‖
W/V, $J \cdot L^{-1}$	1.58 ± 1.15	0.95 ± 0.76§	0.74 ± 0.63‖	0.39 ± 0.14¶

Definition of abbreviations: VT = tidal volume; RR = respiratory rate; $\dot{V}E$ = minute ventilation; Pdi = the difference between peak inspiratory and peak expiratory transdiaphragmatic pressure; $PEEP_i$ = intrinsic positive end-expiratory pressure; $\dot{V}O_2$ = oxygen consumption; $\dot{W}$ = work of breathing expressed per unit of time; W/V = work of breathing per liter of ventilation.

* All data are expressed as mean ± SD. Statistical analysis compares the value with pressure support zero value.

† The mean value for the six patients in whom it was present.

‡ $p = 0.06$.

§ $p < 0.05$.

‖ $p < 0.01$.

¶ $p < 0.001$.

breathing with a parallel decrease of $\dot{V}O_2$ and decreased activity of the inspiratory muscles (figure 2). In Patients 2, 4, and 6, breathing with PS 15 and PS 20 was also characterized by intermittent periods of apnea. The mean values of respiratory parameters, Pdi, and blood gas tensions are listed in table 2. A progressive decrease of Edi and Esm was observed (see below). Respiratory recordings from two representative patients are presented in figure 3. A dramatic reduction of $\dot{W}$ during PS was accompanied by a major reduction of total oxygen consumption in all six patients in whom it was measured (figure 2). A significant correlation was found between COB and $\dot{W}$ during spontaneous breathing at PS 0 ($r = 0.96$, $p < 0.02$). During all conditions, COB and power of breathing were similarly reduced, as shown in figure 4.

In addition, in the six patients in whom it was present, intrinsic PEEP was significantly reduced during pressure support when compared with PS 0 and CMV, with a range from 1.5 to 6.0 cm H_2O during PS 0 and during CMV, and from zero to 1.5 cm H_2O during PS 20. Loops of a representative patient are presented in figure 5, illustrating the gradual reduction of the work of breathing and the decrease in intrinsic PEEP.

Mean HR and BP decreased significantly with PS by comparison to PS 0 and became similar to the values obtained during CMV, with PS 15 and PS 20, respectively.

Estimating the Optimal Level of Pressure Support

Because a reduced H/L ratio is considered as indicative of diaphragmatic fatigue (17), the lowest PS level where no reduction of H/L occurred was taken as the optimal level of PS. At this PS level, the maximal Edi that could be sustained without demonstrating electromyographic signs of fatigue was present. This level was PS 0 for one patient, PS 10 for four patients, and PS 20 for three patients. Individual values of the respiratory mea-

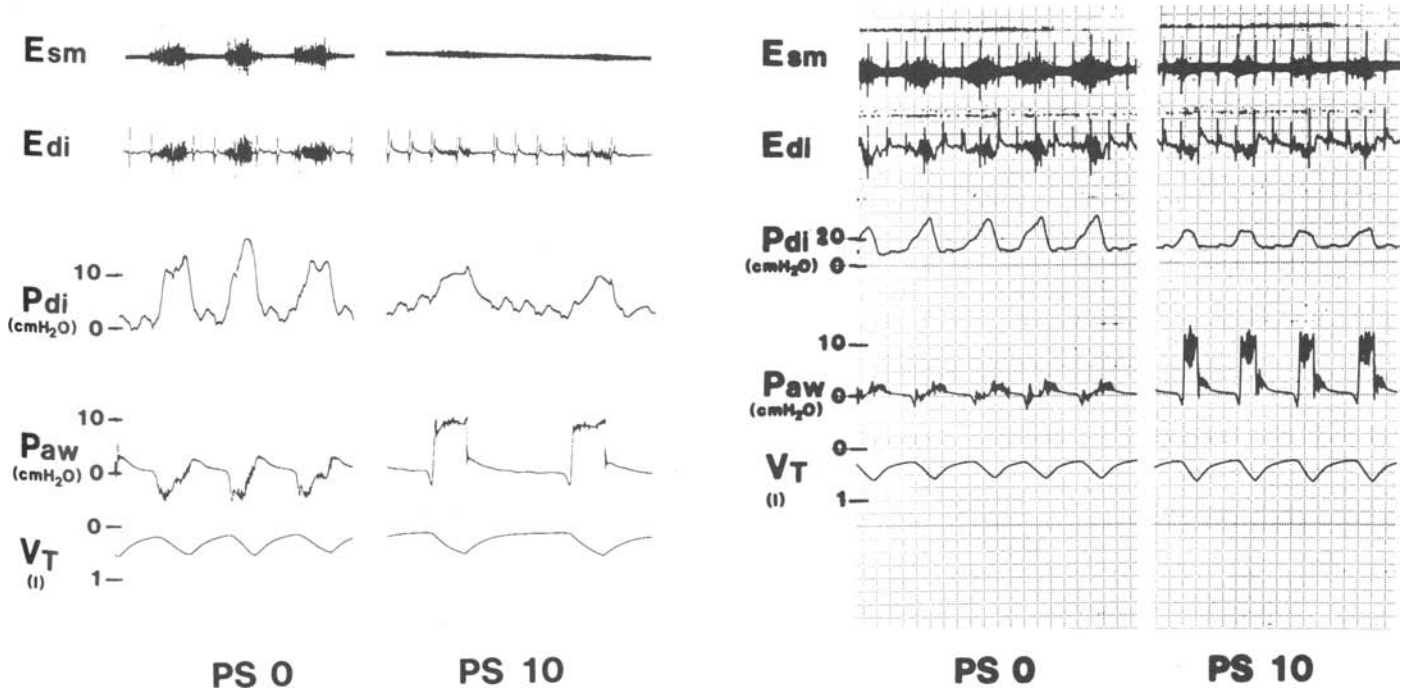

Fig. 3. Recordings of electrical activity of the sternocleidomastoid muscle (Esm) and of the diaphragm (Edi), transdiaphragmatic pressure (Pdi), airway pressure (Paw), and tidal volume (VT) for two representative patients during PS 0 and PS 10. Note that during PS 10, inspiratory Paw is held constant at 10 cm H_2O. Diaphragmatic activity, as assessed by Pdi, is reduced during PS 10, but is still present in the two patients. In Patient 8 (*left panel*), breathing pattern is clearly modified during PS 10. In Patient 3 (*right panel*), PS 10 did not alter significantly the respiratory rate. In this patient, a higher level of PS (20 cm H_2O) was necessary to abolish the electrical signs of diaphragmatic fatigue.

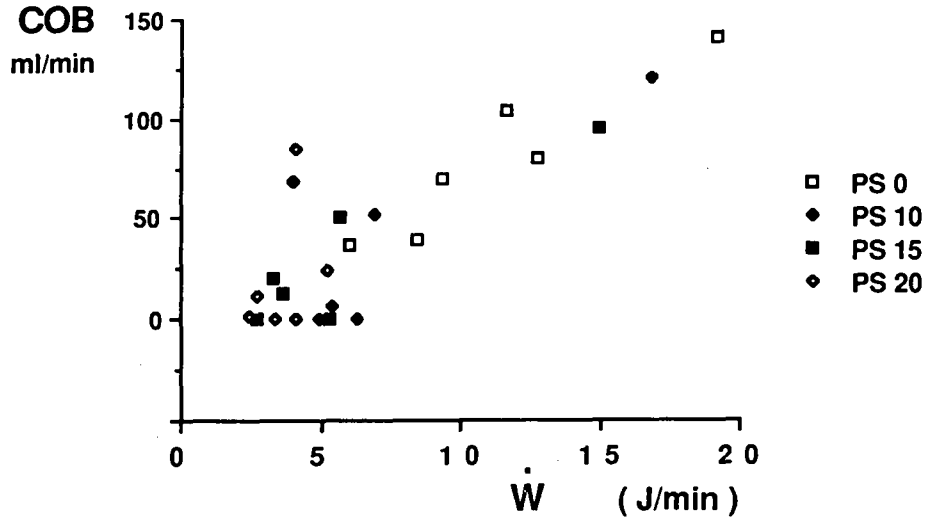

Fig. 4. Overall plot of individual values of power (Ẇ) against cost of breathing (COB) in the six patients in whom it was measured for the four levels of pressure support.

surements at the level of optimal PS are listed in table 3. Interesting similarities were found at this "optimal" level for our patients. The mean values of Ẇ and W/V were 6.26 ± 1.95 $J \cdot min^{-1}$ and 0.52 ± 0.12 $J \cdot L^{-1}$, respectively. Thus, although individual values of the work of breathing during the different modes of ventilation had a very large range, these values were of the same order of magnitude for patients at the optimal level of PS. This is clearly illustrated in figure 6. Above a respiratory work load of about 8 to 10 $J \cdot min^{-1}$, electromyographic evidence of diaphragmatic fatigue appeared, as indicated by a reduced H/L ratio below 80% of initial value. A lower level of respiratory work was always reached at the optimal level of PS.

The changes of Esm at increasing PS levels are shown in figure 5. At the optimal level of PS, Esm fell to the minimal value recorded, which was always below 40% of maximal Esm. The left panel of figure 7 depicts the changes in Esm of the four patients with an optimal PS level of 10 cm H_2O. Increasing PS above this optimal level did not provide a greater reduction of sternomastoid muscle activity. Contractile activity of this muscle was parallel to its recorded electrical activity. At the optimal level of PS, the contractile activity of the sternomastoid muscle was absent or minimal.

Discussion

The main finding of this study was that pressure support ventilation in spontaneously breathing patients prevents diaphragmatic fatigue by diminishing the patient's work of breathing and total oxygen consumption. Moreover, pressure support allows adjustment of the work of each breath to provide a potentially optimal muscle load. An optimal level of pressure support was determined in each patient as the level maintaining maximal diaphragmatic electrical activity without fatigue. At the bedside, clinically monitoring sternomastoid muscle activity accurately defined this optimal level.

Few studies have examined respiratory muscle function during weaning from mechanical ventilation. Cohen and coworkers (2) studied 12 patients with various disorders leading to hypercapnic respiratory failure after discontinuing mechanical ventilation. To detect diaphragmatic fatigue, the power spectrum of diaphragmatic surface electromyographic activity was analyzed. A sustained reduction of the H/L ratio below 80% of the initial value was taken as indicative that diaphragmatic fatigue would ensue. Seven patients showed electromyographic evidence of inspiratory muscle fatigue. "Electrical fatigue" was inevitably followed by respiratory alternans, paradoxical activation of abdominal muscles, and a late reduction of both minute ventilation and respiratory rate with progressive respiratory acidemia. However, only one of these patients had an inspiratory force greater than 25 cm H_2O. Using similar electrical criteria to predict diaphragmatic muscular fatigue in this study, we found that seven of eight patients who met the usual criteria for weaning but who failed to wean from CMV exhibited electromyographic signs of diaphragmatic fatigue during spontaneous breathing. One of our patients (Patient 1) did not show electromyographic signs of diaphragmatic fatigue. His respiratory mechanics probably improved prior to the study, and consequently he was easily weaned and extubated on the day after the study. Thus, we demonstrated that in patients who met the usual criteria for weaning, unsuccessful trials of weaning were associated with diaphragmatic fatigue. Impaired diaphragmatic function during weaning also was implicated by Pourriat and coworkers (4) who studied diaphragmatic function and the pattern of breathing in patients with COPD being weaned from mechanical ventilation after acute respiratory failure. They noted that when Pdi was expressed as a fraction of the maximal Pdi (Pdimax) this value reached a mean of 46% in the group failing to wean. According to Roussos and Macklem (22) a Pdi/Pdimax ratio greater than 40% cannot be tolerated for long periods without fatigue of the diaphragm. Moreover, the ratio of gastric pressure to Pdi, which reflects diaphragmatic effectiveness in the inspiratory process, suggested diaphragmatic fatigue in their patients failing to wean from CMV. Our findings agree with theirs, and the presence of diaphragmatic fatigue is a frequent event in patients failing to wean when disconnected from the ventilator.

Inspiratory pressure support is a novel mode of ventilatory assistance designed to assist spontaneously breathing, intubated patients. Several researchers have shown that this mode of ventilation can diminish the oxygen cost of breathing (23, 24). McIntyre (12) described the ventilatory effects of various levels of pressure support in patients requiring synchronized intermittent mandatory ventilation. He measured a significantly increased tidal volume and decreased respiratory rate when increasing the level of pressure support. Using a physical model mimicking the respiratory system, he demonstrated that pressure support reduced the work of breathing. We have previously reported in patients (11) that a level of 10 cm H_2O of pressure support improved the efficacy of spontaneous breathing while reducing the activity of the inspiratory muscles. In this study, we measured a significantly reduced work of breathing at increasing levels of pressure support. During PS ventilation with a mixture of spontaneous and mechanical work, computing the work of breathing from the esophageal pressure provided an estimate of the elastic and resistive

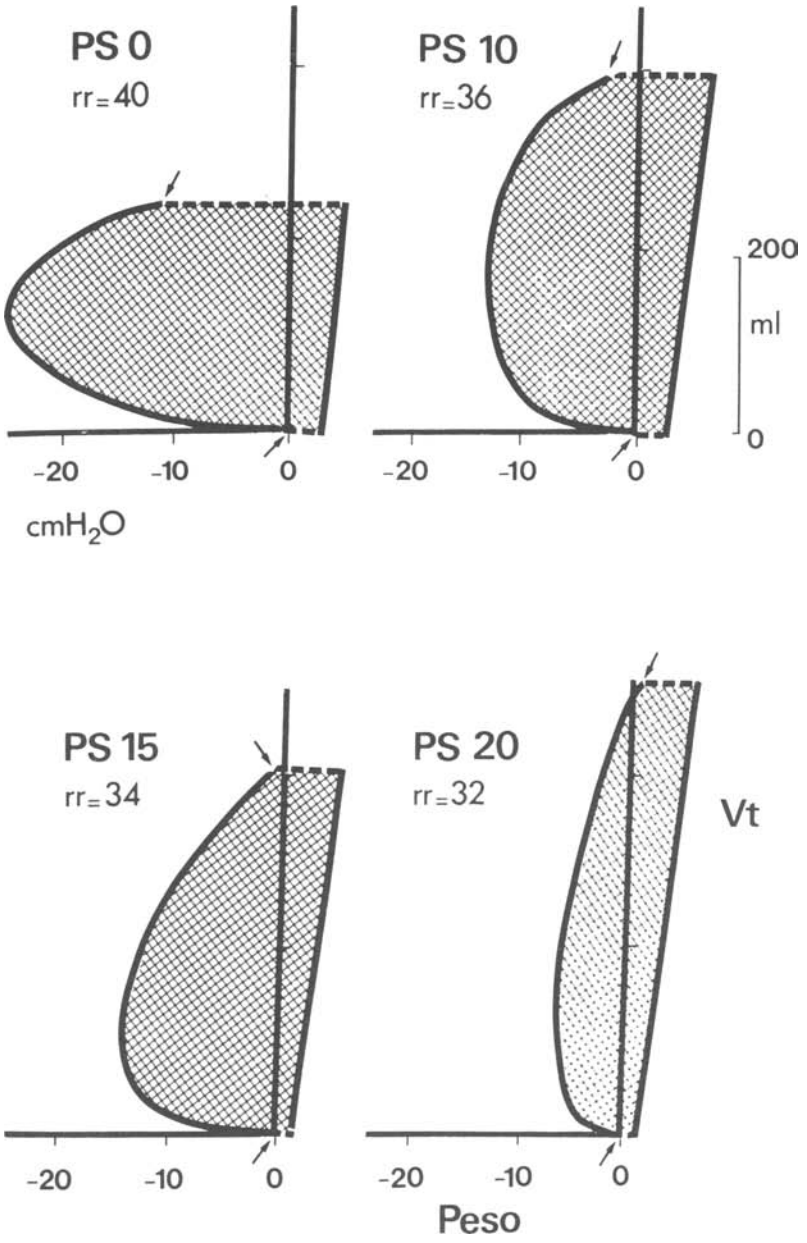

Fig. 5. Loops of esophageal pressure against volume for a representative patient (Patient 7) from PS 0 to PS 20, used for the computation of the work. The work per breath is represented by the hatched area, subtended by the inspiratory part of the P-V loop on the left and the relaxation curve of the chest wall on the right. Arrows indicate beginning and end of inspiration. The relaxation curve of the chest wall is passed through the elastic recoil pressure of the chest at end exhalation and the distance between the beginning of the PV loop (*arrow*), and this relaxation curve represents intrinsic PEEP.

work performed by the respiratory muscles to inflate the lung. Adding pressure support to spontaneous breathing decreased the respiratory muscle work per liter of ventilation as well as the total muscular work per minute, despite the increased minute ventilation.

In addition, an interesting finding was the reduction in intrinsic PEEP or auto-PEEP with pressure support. This was probably due to a decrease in respiratory rate, which allowed a longer expiratory time. It contributed to the reduction of the elastic work of breathing. Although absolute levels of intrinsic PEEP were not very high in these patients, this effect is important in order to facilitate breathing during weaning.

The oxygen cost of breathing was also reduced by adding pressure support ventilation. We found high values of COB during spontaneous breathing via the ventilator circuitry without pressure support, ranging from 10 to 59% of the total oxygen consumption. These values are in agreement with those of previous studies performed in similar conditions (25, 26). From our data, the work of breathing appears to be the prime determinant of the oxygen cost of breathing (27). However, another factor contributing to the increased oxygen consumption may be catecholamine release triggered by the stress of spontaneous breathing. In favor of this hypothesis, we observed a significantly increased heart rate and blood pressure during PS 0.

In a recent study, Tobin and coworkers (28) described the pattern of breathing in patients weaning from mechanical ventilation. Patients who failed to wean were characterized by rapid, shallow breathing similar to the pattern of breathing of our patients without pressure support. Adding pressure support allowed our patients to breathe with larger tidal volumes at a lower respiratory rate, i.e., with a pattern of breathing similar to that in patients successfully weaning in the study of Tobin and coworkers. Moreover, a reduced respiratory drive was determined by electromyographic measurements during pressure support ventilation. This suggests that PS ventilation efficiently assists each breath, thereby allowing the patient to breathe spontaneously for sustained periods.

We selected the optimal level of pressure support as the minimal pressure necessary to prevent electrical evidence of subsequent diaphragmatic fatigue. We examined three arbitrary levels of pressure support in the range of 10 to 20 cm H_2O; it is possible that for some of our patients PS levels below 10 cm H_2O would have been sufficient. We sought to find the lowest possible pressure in the range studied because higher levels of intrathoracic pressure may have deleterious effects such as hyperinflation of patients with high compliance and possibly induced apnea as experienced by three of our patients in this study. Another reason for selecting a low level of pressure support was that inspiratory muscle training may be a useful step towards weaning from mechanical ventilation. It has been suggested that mechanical ventilation leads to atrophy of the inspiratory muscles (29), explaining some difficulties for weaning. Thus, progressive strengthening of weak respiratory muscles may occur without fatigue when using optimal levels of pressure support. Further studies will be needed to test this hypothesis.

The sternocleidomastoid muscles (SCM) are considered auxiliary muscles of inspiration (30). These muscles are

TABLE 3

MAIN CHARACTERISTICS OF THE OPTIMAL LEVEL OF PRESSURE SUPPORT FOR EACH PATIENT

Patient No.	Optimal Level of PS* (cm H_2O)	Pa_{CO_2} (mm Hg)	RR (min^{-1})	VT ($ml \cdot kg^{-1}$)	$\dot{W}$ ($J \cdot min^{-1}$)	W/V ($J \cdot L^{-1}$)
1	0	39	26	6.8	6.0	0.56
2	20	46	28	7.0	8.8	0.59
3	20	39	35	9.4	4.1	0.31
4	10	36	22	9.3	6.3	0.53
5	10	34	27	4.7	6.9	0.68
6	10	36	20	8.4	4.9	0.46
7	20	38	32	8.8	9.2	0.60
8	10	40	24	9.2	4.0	0.40

For definition of abbreviations, *see* table 2.

* The optimal level of pressure support (PS) was defined as the lowest level without electrical signs of fatigue. For further explanation, *see* table 2 and text.

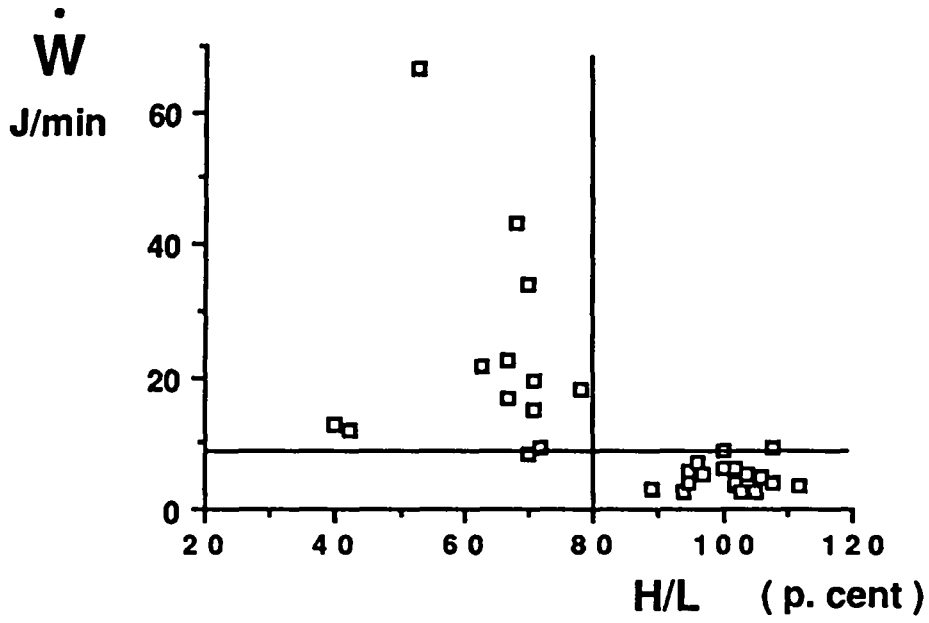

Fig. 6. Plot of individual values of the power ($\dot{W}$) against H/L ratio at the end of each run for all levels of pressure support. H/L was expressed as a fraction of its initial value in each period. Two regions can be distinguished: (*1*) above a certain amount of $\dot{W}$ (*horizontal dashed line*), values of H/L were in the zone of fatigue (*vertical dashed line*); (*2*) below this level of $\dot{W}$, no evidence of fatigue occurred.

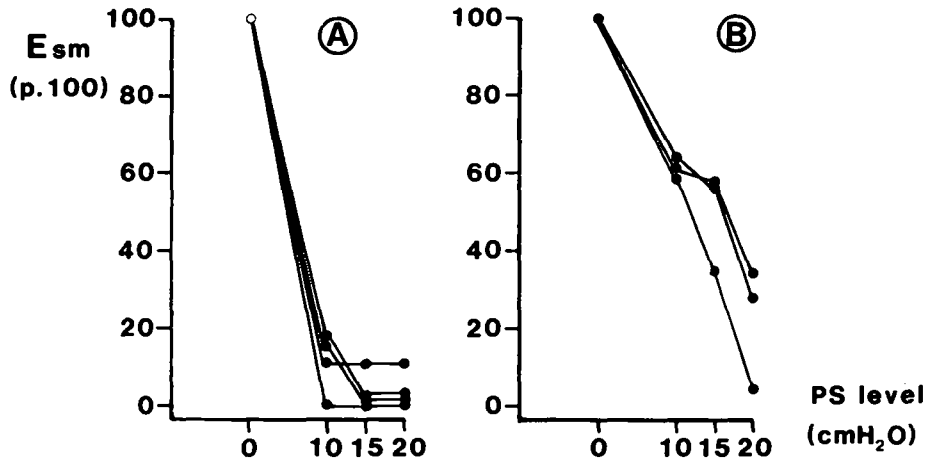

Fig. 7. Individual values of the electrical activity of the sternocleidomastoid muscle (Esm) for the four levels of pressure support. Activity during PS 0 is 100%. The left panel represents the four patients with an optimal level of 10 cm H_2O. Note that at higher levels of PS, Esm was not further reduced. The right panel represents the three patients with an optimal level of 20 cm H_2O.

readily accessible for direct palpation or for electromyographic studies. In healthy subjects, they are inactive during spontaneous breathing at rest (31). In patients with pulmonary emphysema, phasic inspiratory activity is often measured during spontaneous breathing (30). We found that the electrical muscular activity of the sternomastoid muscle was greater when the diaphragm was under a fatiguing load. The activation of the SCM was concomitant with an increased demand for ventilation. Pressure support ventilation decreased the activity of the SCM while decreasing the total work of breathing. At optimal PS levels, the SCM had minimal electrical activity (absent activity in patients without COPD). Patient 1 did not demonstrate diaphragmatic fatigue and never exhibited activation of the SCM. We suggest that monitoring pressure support ventilation could be done at the bedside by palpating the muscular activity of the sternomastoids. Pressure support should be gradually diminished until the phasic inspiratory activity of the sternomastoid muscle appears to increase. Then a slightly higher level should be applied, avoiding fatigue on the one side and overdistension and apnea on the other side.

In conclusion, we have demonstrated that pressure support ventilation is able to prevent diaphragmatic fatigue during weaning from mechanical ventilation while allowing spontaneous activity of the diaphragm. Regulation of the pressure support level varies the amount of work performed by the patient. An optimal level of PS can be found, balancing the need to maintain substantial diaphragmatic activity as required during weaning from mechanical ventilation, and avoiding diaphragmatic fatigue.

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